# Scaler System Testing in the HAWC Experiment

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Abstract: TeV gamma rays probe the non-thermal Universe in ways that are not possible at other wavelengths. The HAWC observatory, under construction in Mexico, will be able to analyze and survey the TeV sky more completely than any competing detectors that use air Cherenkov techniques, and perhaps yield new insight onto the nature of cosmic accelerators responsible for gamma ray bursts, active galactic nuclei flares, and other cataclysmic astrophysical events. Before it's deployment, one of HAWC's electronic data acquisition systems, the scaler system, will be tested using a pulse generator. The pulse generator's capabilities are assessed and documented.

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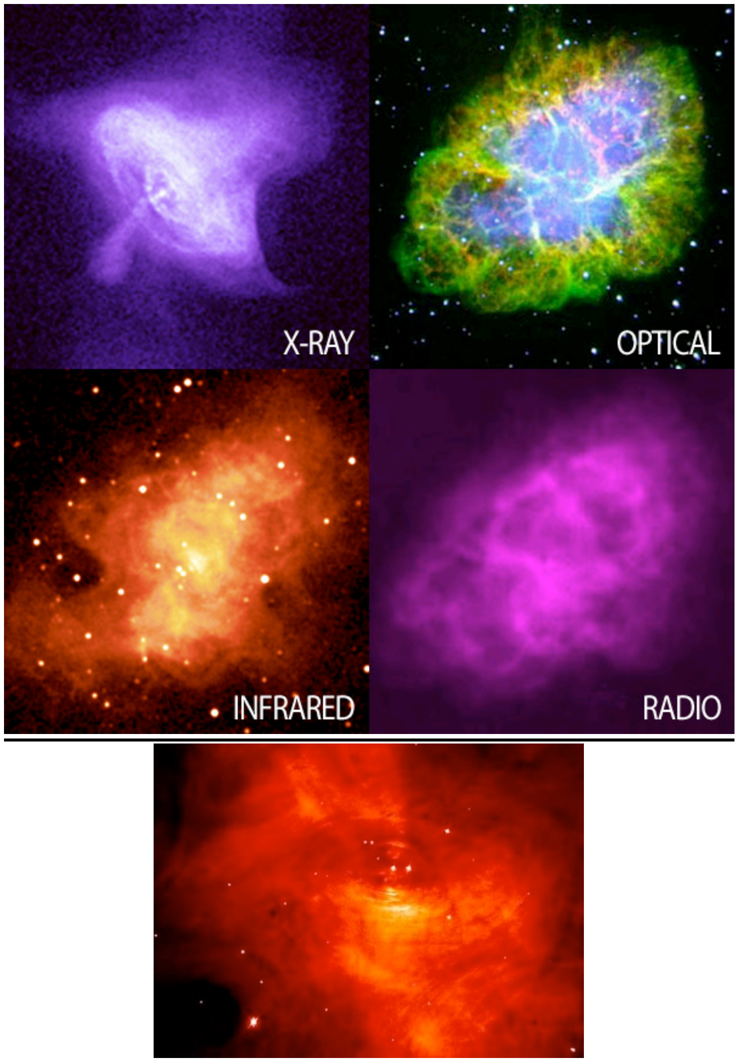


**Figure 1: The Crab Nebula in the x-ray, optical, infrared, radio, and gamma ray spectrum (in order). Images from the Chandra x-ray Observatory. [15]**

# Introduction to Gamma-Ray Astronomy

## 1.1 What is Gamma-Ray Astronomy?

Scientists who study astronomy and astrophysics have often faced a single glaring question which not only makes it difficult to raise public support, but also at times makes it nearly impossible to even continue to study a given topic. This question is as follows: "Why do we care?" Although the question is simple in both structure and scope, it's very difficult to honestly and concisely answer. This is because astrophysics is the study of things *very* far away which at the most seem to only affect the everyday lives of people in a sort of wont and obvious way. For example, one need not know the elegance of Einstein's general relativity or "look forward to the possibility of tests of strong-field gravity in the vicinity of black holes and neutron starts" [1] to know that the stars will still be where they are now, mostly unchanged, each night for the next thousand years and beyond. Nonetheless, numerous mathematicians, physicists, and astronomers are willing to devote their entire life's work to find out why the stars remain only 'mostly' unchanged. These people from around the world recognize, as we shall see, that in fact the universe is full of exciting, dynamic, and even violent events that rack the entire night sky. The reason why the stars appear deceptively tranquil is because many of these cataclysmic events are invisible to all but the most sophisticated equipment. In fact, scientists from around the world have remained oblivious to the storm of energetic particles bombarding the Earth for most of human history. It is only in modern times that this phenomenon has been identified [2]. It therefore seems prudent - and even pressing - to understand as much as we can about these periodic invisible radiation storms and its cosmic sources. Particularly, physicists and astronomers from around the world have come together to form the High Altitude Water Cherenkov (HAWC) Collaboration. This new experiment in the field of astrophysics promises to shed light on numerous ill understood phenomenon including Gamma Ray Bursts, map extrasolar gamma ray sources, and, in general the TeV sky continuously and completely.

Before that, however, it is necessary to ensure that the reader has, at least, a minimal knowledge of what gamma ray astronomy is and why it is important to physics. A gamma-ray is an electromagnetic wave exactly similar to light or radio waves; the only characterizing difference is that gamma-rays have a higher energy than light or radio waves. In fact, gamma-rays have the most energy of any other electromagnetic excitation; a high energy (HE) gamma ray has an energy upwards of 10^9 eV (1 GeV) and a *very* high energy (VHE) gamma ray can have energies of above 10^12 eV (1 TeV) or even, for ultra high energy (UHE) gamma rays, 10^15 eV(1 PeV)! Gamma-rays are invisible to the naked eye – however, their effects can be seen with the appropriate equipment. By extension, gamma-ray astronomy is simply the observation of the universe using telescopes, satellites, and all of the various things that one traditionally associates with astronomy except that we view the gamma-ray spectrum instead of the visible spectrum.

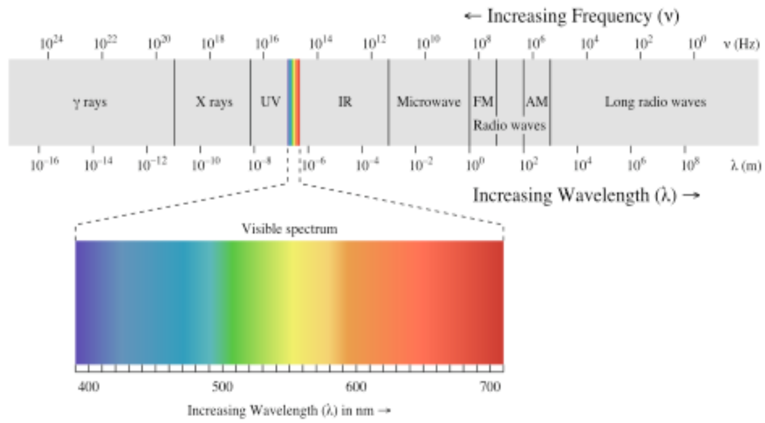


**Figure 2: The electromagnetic spectrum in order of increasing wavelength. Gamma rays is the band to the far left.**

To date, over 100 sources very high energy gamma rays have been documented. This is the result of the spectacular advancement of the field over the course of the last 20 years; in 1989 there was one known source (the crab nebula) and even in 1999 there were only three [3].

## 1.2 Types of Sources

Most very high energy sources can by placed into one of five classes: supernova remnants, pulsar wind nebulae (PWN), unidentified objects, gamma-ray bursts, and active galactic nuclei. The first three of these classes reside within our own galaxy and are steady sources of gamma rays. Supernova remnants are the remains of a massive star which at the end of it's lifespan exploded in a single brilliant flare. The aftermath of these explosions is a brilliant cloud of gas that can emit gamma-rays for many centuries. Pulsar wind nebulae are similar to supernova remnants except that there is a pulsar at the center of the cloud. Here, the pulsar wind is slowed to sub-relativistic speeds causing gamma-ray emission. A source can be classified as unidentified because it might be a steady gamma-ray source that has no visible, x-ray, or radio counterpart; that is, it comes from a part of the sky that is 'dark' in the visible spectrum – it is simply a mysterious signal coming from otherwise dark space. Alternatively, an unknown source could be in an area so dense with sources at other wavelengths that it is impossible to tell which source actually caused the gamma-ray emission.

**Figure 3: An example of a PWN and supernova remnant. [2]**

Gamma ray bursts and active galactic nuclei reside outside of our galaxy. Active galactic nuclei (AGN) are supermassive black holes at the core of distant galaxies that, for an unknown reason, are consuming and emitting energy at an astonishing rate. A gamma ray burst (GRB) is a sudden pulse of high energy photons that briefly comes from a single spot in the sky. They are classified into two sub categories: short duration events (<2s), and long duration events (>2s). The Gamma-Ray Burst Network attempts to alert observers around the world of GRBs as they are detected by dedicated satellites, allowing ground based observatories to quickly realign their telescopes so that the GRB may be observed. Data acquired in this manner suggests that long duration GRBs are most likely caused by supernovae. Short duration GRBs remain poorly understood in part because of their characteristically short timescale.

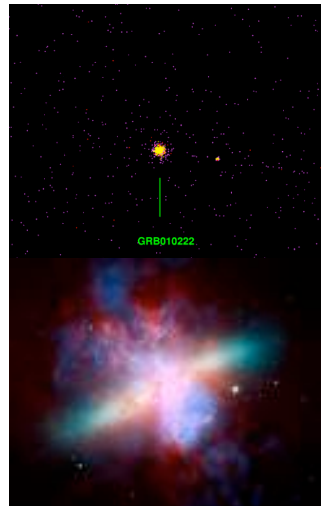


**Figure 4: An example of a GRB and a false color image of an AGN. [2]**

A large amount of time and energy has been used to attempt to characterize and explain the mechanisms that cause GRBs. For example, Shibata and Taniguchi argue convincingly that binary neutron stars in close orbits who merge to form a black hole is the central engine of short duration GRBs [4]. Numerous other possibilities have been proposed as well.

Whatever their cause, many sources of VHE gamma-rays are also possible sources of cosmic rays. Cosmic rays are relativistic charged particles kicked off of unknown energetic sources. When these quickly moving particles collide with another object, they can give off some of their energy in the form of gamma rays. Thus Gamma-ray bursts, as well as all galactic and extra galactic gamma ray sources may, at some point, come from an accelerating cosmic rays near its origin. Observing the high energy spectrum for steady and transient sources of gamma rays is an essential probe of cosmic rays and their sources for this reason [5].

## 1.3 Detection Devices: Overview

To date the field is dominated by imaging atmospheric Cherenkov telescopes (IACTs), however there are many other types of detectors that have been created and are in development. In the following few paragraphs, the full range of these devices will be reviewed and discussed.

To study cosmic rays and the things that produce them, it quickly becomes apparent that one can only make observations and design experiments to study them indirectly. This is because cosmic rays are relativistic protons, nuclei or some other charged particles created in still unknown cataclysmic cosmic events, like possibly pulsars and supernovas [6]. Since they are charged particles they interact with galactic and intergalactic magnetic fields and their directional information is lost. Indeed, theoretical evidence suggests that the mean free path of cosmic ray electrons and protons are quite low – being typically smaller than the thickness of the Milky Way; in many models they rarely make it out of the mechanism creating them [7]. Once these particles do interact, however, they produce something useful to us: gamma rays.

In 1952 Sachio Hayakawa predicted that a cosmic ray that collides with interstellar gas produces neutral pions which then decay to produce gamma rays [2]. Gamma rays have the advantage over cosmic rays that they do not bend in magnetic fields – thus their source of origin can be traced. By observing the energy, incident angle, and spatial distribution of these gamma rays when they reach Earth it is possible to constrain the types of phenomena that could have produced them and thus the conditions that created the cosmic rays [5]. Armed with this information, numerous devices have been developed to observe extrasolar gamma rays. These devices come in two types: either they are based in space and designed to collect incident gamma rays directly as they stream to the Earth, or they are ground based.

One of the most notable of the former variety is Compton Gamma Ray Telescope which was launched in April 1991 and it's Energetic Gamma Ray Experiment Telescope. As recently as June 2008 the Fermi Gamma-ray Space Telescope was launched and promises to be the new flagship of space borne gamma ray detectors [8]. These satellites have firmly developed high energy gamma ray astronomy as a new astronomical domain. The primary drawback of these devices is that space borne detectors must keep a reasonably small payload – and thus a low effective collection area. This puts limits on

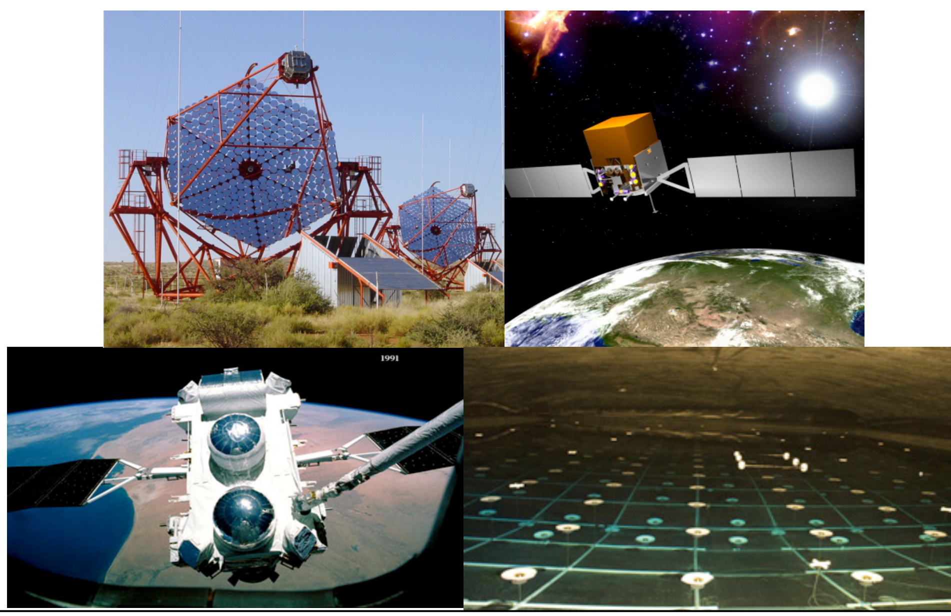


**Figure 4: Hess; a computer image of the Fermi Gamma Ray Space Telescope; The Compton Gamma Ray Telescope; the inside of Milagro. [8] [14]**

the range of possible energies that can be readily observed [9]. Thus ground based devices have become the favored method of very high energy gamma ray observation.

## 1.4 Focus: Ground Based Detectors

For ground based gamma ray detectors, it is highly unlikely that the gamma ray being observed will ever make it to the ground. Instead, the incident gamma rays entering the Earth's upper atmosphere will collide with air molecules. As they do, the gamma ray will be absorbed and spontaneously create an electron and a positron through a well understood quantum mechanical process called pair production. Both particles will travel a short distance before colliding with a nearby molecule. This collision will produce a new gamma ray (although less high energy than before) via a process known as Bremsstrahlung. This set of events will repeat itself until there is not enough energy to create further particles. The resulting cascade of energetic charged particles is called an Extensive Air Shower (EAS). This process is well understood:

> The number of electrons at the point of maximum development of the cascade is closely proportional to the primary energy and the atmospheric depth of this maximum increases logarithmically with energy. For a 1 TeV photon-initiated air-shower this maximum occurs at a depth of ~300 g cm^-2 or a ~10 km above sea level (a.s.l) for a vertically incident photon. Electrons and positrons in the shower with energies greater than $m_e c^2 / \sqrt{1 - n^{-2}}$ [w]ill emit Cherenkov light. [10]

The Cherenkov light mentioned can be observed directly with the appropriate equipment and it is by analyzing this light that inferences can be made about the incident gamma ray and thus the source cosmic ray that caused it. This is the method used by IACTs to do gamma ray astronomy. In a way it's analogous to using the Earth's atmosphere as a 'lens' to view high energy extrasolar photons.

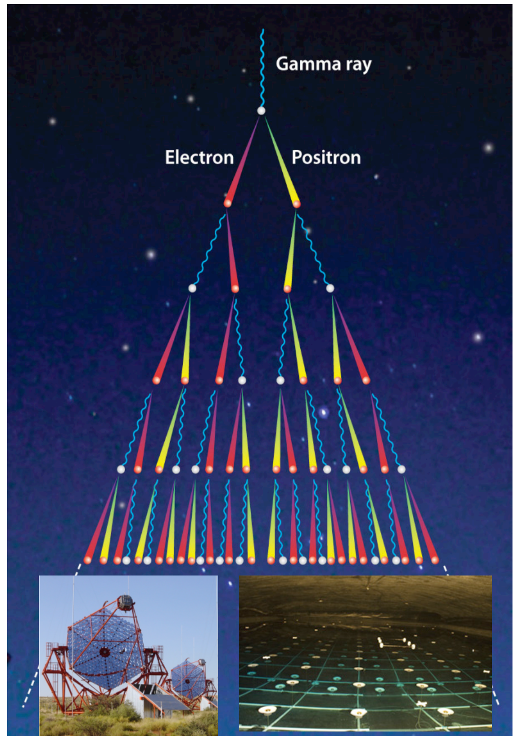

**Figure 5: An EAS Shower illustration. [14]**

Unfortunately, these types of detectors have several limitations. For example, they can view only narrow portions of the sky at a time (about three degrees) and then only for relatively short periods (~10% duty factor) because of their sensitivity to the lunar cycle, the weather, and the sun [10]. Nonetheless, IACTs have provided the excellent sensitivity and well resolved images required to bring our understanding of astrophysics to where it is today. As such, they have been responsible for the discovery of approximately 90 of the 100 very high energy sources currently known.

Numerous powerful IACTs are presently operational. HESS is an array of four Cherenkov telescopes in Namibia. Each telescope is 13 m in diameter and has a focal length of 15 m. In each telescope is a camera that consists of 960 photomultiplier tubes (PMTs) that can be used to detect Cherenkov radiation. The MAGIC telescope in the Canary Islands has only two telescopes, but they are 17 m in diameter and thus the largest

Cherenkov Telescopes in operation. As such, it also has the lowest trigger level energy threshold (about 25 GeV) of the ground detectors. VERITAS is an array of four 12 m telescopes at the Whipple Observatory in Arizona. In many ways it is similar to HESS, but boasts a much faster camera. A number of smaller IACTs such as the CANGAROO-III, TACTIC, and PACT systems remain operation and take data around the world [10].

There exists, however, a second class of ground based detector. They are EAS detectors; named after the extensive air showers mentioned earlier. Unlike IACTs, EAS detectors do not attempt to observe the Cherenkov light coming directly from the sky. Instead they are built at a high enough altitude to allow the charged particles of an EAS to enter directly into a detection device filled with some known medium (such as a water tank as shall be discussed). Once inside the device, the charged particles once again emit Cherenkov radiation, but this time it can be observed without bias from the rest of the sky. In the case of HAWC, this will prove to be very useful.

## 1.5 Milagro

Two of the most successful EAS detectors to date are: Milagro and Tibet AS. Milagro in particular warrants special interest within the scope of this paper because of it's relatedness to HAWC. This experiment is HAWCs spiritual predecessor and in many ways the lessons learned from Milagro have heavily influenced HAWCs design. Milagro consisted of a single large pond of water with PMTs evenly spaced along the bottom of the pond, and was based at the Los Alamos National Labs in New Mexico. Whenever an EAS shower caused charged particles to stream through the water in the pond at speeds greater than the speed of light in water, cones of Cherenkov radiation would trigger the

PMTs in observable patterns [10]. Although this was highly successful, Milagro had a distinct design flaw: since there existed only one pond, the Cherenkov light in the pond reflected and interfered with itself causing poor resolution and blurry images. In addition, the detector was a somewhat small 60x80 meters with a 200x200 m outrigger, which meant that it had difficulties reconstructing the direction of photons. It also was at a low altitude, 2650 meters above sea level, effectively increasing the amount of atmosphere between it and any incoming EAS and thus allowing the EAS to become weaker and less easily observed [11]. Nonetheless, Milagro made several useful discoveries; it observed and cataloged 6 sources that had not been previously reported and confirmed the existence of 12 additional sources reported by other detectors. Milagro also discovered an unexpected anisotropy of ~10 TeV cosmic rays. That is, it found cosmic rays arriving unequally from different directions in the sky.

In the future, the HAWC experiment is a new EAS detector which will enable very high energy gamma ray studies that are unattainable with the traditional IACTs. HAWC has the advantage over IACTs that it allows a continuous and simultaneous survey of a large fraction of the sky. While HAWC will not match the sensitivity of IACTs, it will be sensitive enough to highlight areas of interest and alert IACTs to make a more complete observation. HAWC will be able to observe AGN flares and GRBs from the moment of their onset and in greater numbers than any other instrument to date. Finally, HAWCs lifetime observations will allow astrophysicists to put strict limitations on the types of phenomenon responsible for the acceleration of cosmic rays [5].

Additionally, construction of HAWC has already begun on site in Mexico. The first six tanks for HAWC have been bought and they will be assembled by the end of May, 2010.

## 1.6 Final Comment

If the advancement of our understanding of physics is still not enough to emphasize the weight of gamma-ray astronomy and now the HAWC Experiment, then consider this: exploration of space is quite impossible without understanding the dangers and phenomenon that dominate there. Indeed, there is some evidence to suggest that a GRB within the Milky Way (estimated to occur about two every billion years) contributed to one of the five mass extinctions in world history [12]. Still, it is perhaps not fair to discuss gamma ray astronomy in this way. While a danger does exist from spectacular galactic explosions and events, empirical evidence should show that this danger is distant. Rather, gamma-ray astronomy presents the ability to study and understand the fantastic and curious phenomenon that pervade the galaxy within the safety of Earth.

Figure 6: HAWC site at Sierra Negra with an artist's conception of the 300 HAWC tanks overlaid to show the location of HAWC. The volcano Pico de Orizaba is visible in the background (Aguilar et. Al 2008).

# The HAWC Experiment

The High Altitude Water Cherenkov (HAWC) experiment aims, at it's most basic level, to observe the acceleration of cosmic rays by simultaneously and continuously surveying nearly the entire northern sky for high energy sources of gamma rays. This is fundamentally different from IACTs because HAWC can view a large portion of the sky with almost 100% duty cycle while IACTs struggle with a narrow field of view and small duty [5].

## 2.1 HAWC's Physical Layout

Like Milagro, HAWC makes use of large tanks of water with photomultiplier tubes (PMTs) lining its bottom, however HAWC takes a new tactic. Instead of one large pool of water, HAWC uses many optically isolated tanks of water arrayed in a two dimensional lattice. Each tank is commercially manufactured and built out of corrugated steel with a black plastic bladder lining the inside. This allows photons that are not detected by the PMTs to be absorbed by the tank – reducing late detections and meaningless noise. When completed, HAWC will consist of 300 tanks, each 7.3 meters in diameter and 4 m tall with three PMTs anchored to the bottom each tank (900 total). HAWC will reuse the 8" Hamamatsu PMTs from Milagro and space them evenly along the base of each tank.

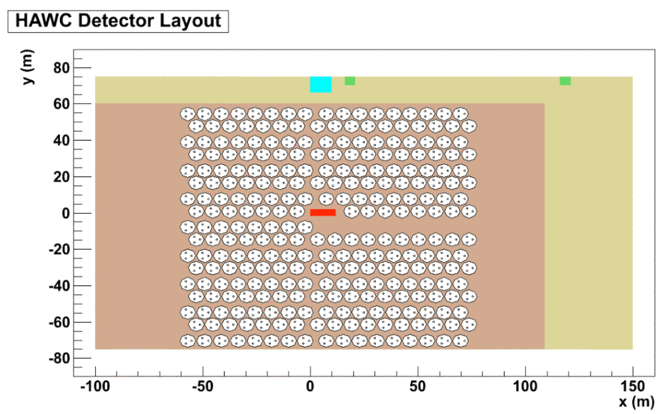


**Figure 7: Graphical representation of HAWC's layout.**

The tanks will be set up in a dense rectangular pattern of about 150x135 meters with ~66% instrumental coverage. Since each tank serves as its own EAS detector, the setup will be analogous to the functionality of a digital camera: each tank or 'pixel' stores its own energy and temporal data. Afterwards, the data can be pieced together to form a coherent image that will be interpreted to provide information about the source gamma ray; this will be discussed in depth later. In addition, the entire project is designed to be scaleable. That is, tanks can be added and deleted as technical and budget conditions evolve. In the future, the spacing of the tanks and the number of PMTs per tank may be

Figure 7: Prototype tank for use in HAWC.

altered to directly effect the energy threshold and other technical specifications of the device. This gives researchers freedom to control what sorts of things they want HAWC to look for. In summary, HAWC is designed to be a high efficiency highly flexible EAS detector with an initial effective area of 20,000 m^2.

The detector is to be located at the Parque Nacional Pico de Orizaba, Mexico. It will be nestled in the saddle between Pico de Orizaba (the highest peak in Mexico – 5610m) and Sierra Negra (4600m), immediately adjacent to the Large Millimeter Telescope on top of Sierra Negra. The near equatorial location means that HAWC will observe a large fraction of the northern sky (15% more within a 45 degree field of view than Milagro). It also means that its visible range will overlap both spatially and temporally with many important observatories in the US, Mexico, and Chile, allowing HAWC to alert these observatories of any interesting phenomenon quickly and can aim to simultaneously observe these objects as they happen. Furthermore, HAWC will be at an altitude of 4100 meters above sea level (a great improvement over Milagro) allowing HAWC to be nearer the origin of the EAS showers. This is useful because EAS showers lose energy (and thus component particles) as they descend, so clearly being

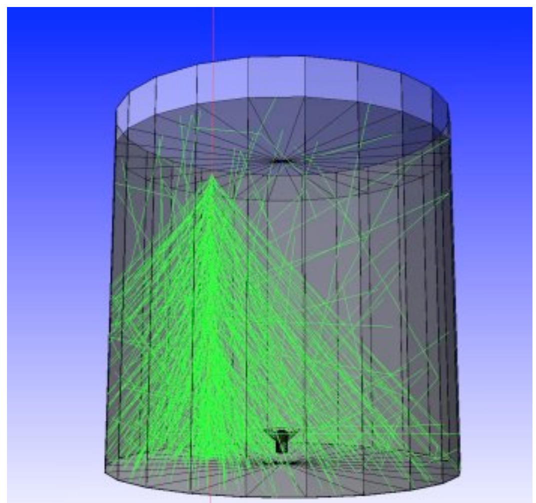

Figure 10: A 5 meter diameter tank as simulated in Geant4 for a single verticle muon. The number of photons are reduced by a factor of 50 for visualization (Aguilar et. Al 2008)

closer to the shower maximum allows for a larger number of particles that can be captured – and thus better detection.

HAWCs proximity to the Large Millimeter Telescope means that a great deal of needed infrastructure has already been installed. Namely, electricity, internet, water, facilities, electronics, and a road have already been constructed to access the site. Experience from the LMT has also already suggested many methods of handling the weather in the region.

## 2.2 Data Acquisition: The Trigger System

Once an EAS causes a PMT to trigger, a large system of electronics are responsible for putting that signal together into a coherent and useful form. Indeed, HAWCs design will allow for the PMTs to easily and effectively gather huge quantities of data that can be then interpreted to provide information about gamma rays and their cosmic ray progenitors. To help process this data, HAWC will make use of a complex triggering system called the Data AcQuisition systems (DAQs) that will statistically analyze the information coming from the PMTs for event significance; allowing the researchers to only view important or interesting data. There are two DAQs: the trigger system and the scaler system. The former has the responsibility of pinpointing the origin of a single EAS shower while latter will only specify the likely presence of an event *somewhere*, after that it is the responsibility of the researchers or other electronic systems to specify where an event is occurring and what sort of event it is. This is particularly true of transient phenomenon since a constant source will not induce any useful change.

As described earlier, the trigger system's only task is to deduce information about a single EAS. As the chain reaction that makes up an EAS propagates through the atmosphere, the charged particles of the air shower will have so much energy that they will all be moving near the speed of light. As such the front end of the shower lines up in a single plane perpendicular to the trajectory of the EAS. When this pancake of particles reaches the surface of the Earth it is unlikely to be aligned parallel to the ground, so one edge of the cascade reaches the ground first and the opposite edge reaches the ground last. The trigger system takes in the data coming from each PMT and looks for the temporal variation that would indicate such an effect. Then the system analyses this time shift and uses it to calculate the original trajectory of the EAS shower – and thus it's gamma ray progenitor.

## 2.3 Data Acquisition: The Scaler System

The trigger system is very useful for analyzing a single EAS shower, but showers come from different places in the sky continuously so it is sometimes more useful to know if there is an interesting change somewhere than simply the full state of the sky. This obviously pertains to the search for transient events, like gamma ray bursts. The scaler system is expressly for this purpose. Whereas the trigger system analyses an individual EAS for it's directional information, the scaler system analysis the status of *all* recent EASs to look for some sudden change.

The PMTs will have a natural firing rate of around 20 kHz (about 180,000 counts for all 900 PMTs in 10 milliseconds) because of a number of factors including natural radioactivity, thermal noise, cosmic rays from the sun, steady astrophysical sources of gamma rays, and so on. To save and view all of the information that the PMTs transmit would be technically difficult and a drain on resources. Instead the scalers look for sudden and otherwise unexpected spikes in the sea of counts. If these spikes are statistically significant to some predetermined confidence interval (that is, if the spike is sufficiently large), then the scaler systems knows it is looking at something interesting. This statistical significance is denoted by sigma which is calculated by taking $Sig \approx \frac{N}{\sqrt{B}}$, where N is present number of counts in all PMTs and the typical background, B. The background is equal to 0.01 s times 20,000 kHz times 900 PMTs. If Sigma exceeds five, the signal assumed to be real. This is expected to be around a 5 Hz jump in the count rate (~425 more counts per PMT per 10 milliseconds than normal). Once all 900 PMTs are analyzed in this way, a coherent picture begins to emerge – namely, that there has been some event; a number of gamma rays are suspected to have struck the upper atmosphere. It is the responsibility of the scaler system to do this nearly instantaneously so that an alert may be sent out to other laboratories around the world. HAWC may then begin to interpret the observations using another detection system to point out where in the sky the event happened and thus other researchers may view the observed change as soon after its onset as possible. The major result of all of this is that HAWC will be able to differentiate point sources of gamma rays only about a degree apart due to this necessarily powerful tool.

# Data and Analysis

## 3.1 Testing the Scaler System: The Pulser

Within the HAWC collaboration, my laboratory is responsible for building and ensuring that the electronics and particularly the scaler software develop properly. It has been my task to develop the software needed to operate an internal pulse generator capable of pulsing at a rate that one might expect to find coming from the PMTs. This pulser could be used to feed known data into the scaler system as a sort of 'dummy PMT'. By modifying this signal in a systematic way, the pulser could be used to test the scaler system's statistical analysis software prior to the deployment of the electronics in Mexico.

The internal pulse generator is named such because it is designed to function as a module within the scaler architecture. From a computational perspective, it is operated by a class that modifies and operates a specialized set of electronics solely responsible for generating a square wave signal with a known frequency and width. To assist in this task I have learned to program in C++ and have developed limited capabilities in ROOT, the leading analysis software of particle physics.

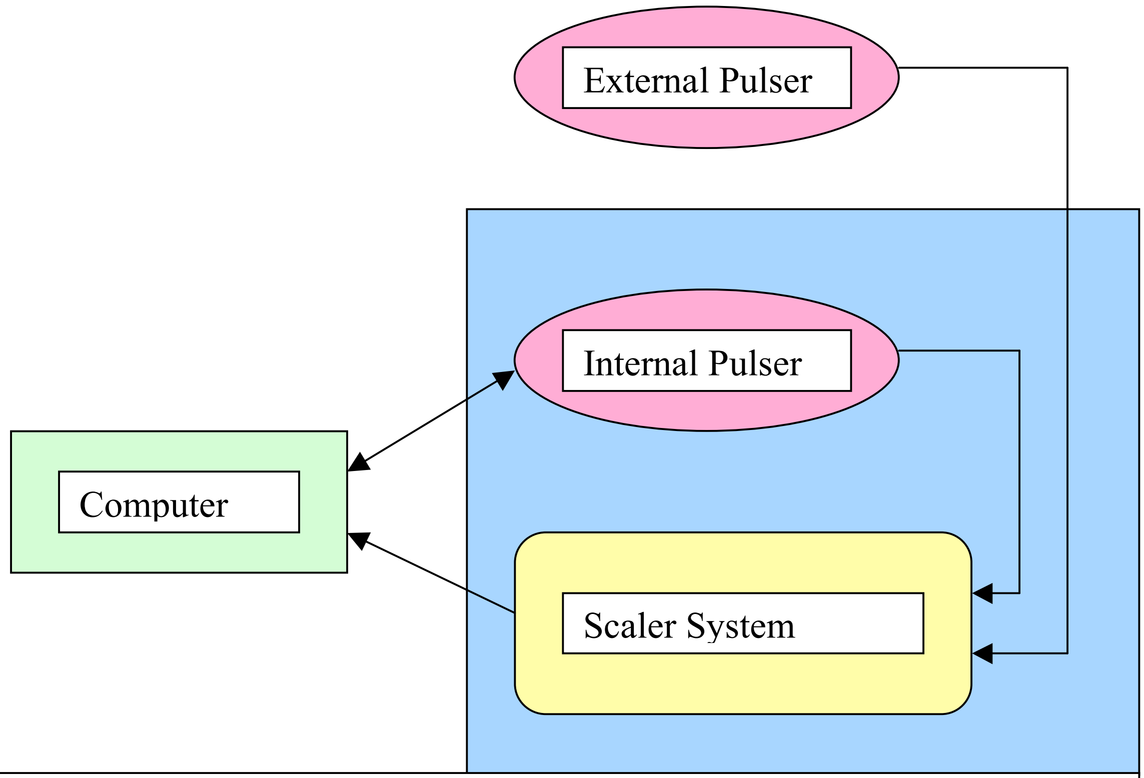


**Figure 11: Map of pulser setup.**

As stated, the pulser is a device used to create a square wave electrical signal with variable frequency, pulse width, and even a 'burst' (the pulser creates the signal for a fixed number of pulses). My pulser's period can be set to a discrete set of values separated by 100 nanoseconds and between 100 nanoseconds and 3.36 seconds. It's width can be set from 20 ns to 1.31 ms in increments of 20 ns. In addition, it can be set to pulse continuously or in bursts of less than 2^32 pulses. In other words, the pulser is an electronic clock that pulses (or ticks) at a known rate. If this simple fixed signal is analyzed by the scalers, it should be immediately apparent to software that the incident signal is regular and thus atypical of what one would expect to see coming from a real PMT. As such, it behaves as an adequate early test of the prototype scaler's functionality.

Of course, both the pulser can create signals at an astonishing frequency – a single pulse may be as brief as 20 ns. If the pulser is even one nanosecond 'fast' at the end of 20 ns, this inaccuracy may build very quickly to a volatile scale. In the case of this example, after only 200 ns the pulser would become most untrustworthy because it could be entirely out of phase with a proper signal. Thus, it is necessary to also test the pulser for stability. That is, I have been responsible for ensuring that the pulser behaves in the way that it is programmed to behave without pulsing too slowly or too quickly. Unfortunately, if one simply compares the output of the internal pulser to another clock, the problem becomes a convolution of the accuracy of the two clocks instead of a proper test of the internal pulser. In other words, if the pulser and external clock do not agree that a set amount of time has passed it is impossible to tell if it is the internal pulser or the clock that is incorrect. For example, the internal clock on some personal computers, which keeps track of the time on a microsecond scale, have been known to drift as much as 10 seconds in a single day.

To try to solve this problem, I have also modeled numerous long (>300,000 data points) trials of the internal pulser against an external pulse generator available in the lab to test the stability of the pulser. While it is true that the data acquired will be a convolution of the two signals, numerous long tests varying the frequency of both clocks will allow me to deduce what the critical timescale is when the two clocks stop agreeing on the time. In the following section I will present my findings and conclusions.

Of course, it would be ideal to have a 'trusted' clock the compare the pulse generator against. To this end, I have since added a network time protocol (NTP) stamp onto each comparison. The NTP is an internet application that takes in time data from a large number of client computers and averages that data to find a time that is most agreed upon by all the clients. This time is trusted as accurate. Similarly, HAWC will make use of an even more accurate GPS clock on site. Thus in both cases, an accurate time can be observed, but nonetheless comparing the two pulsers will provide useful information about these pulsers until a better, more reliable method can be implemented.

## 3.2 Pulser Stability

To help analyze the stability of the internal pulser, I compared the output signal of my pulser with the output of an external pulse generator. Each pulser functions like a clock and 'ticks' as a stochastic random process with both clocks independent of each other. A computer was used to find the number of pulses that occurred in the internal pulse generator between any two consecutive pulses of the external pulse generator. One resulting integer was called a trial. This setup was chosen instead of its opposite because the internal pulser could be set to a much higher frequency (10 MHz) than the external pulser (~100 kHz). Six frequency comparisons were made with at least 10^4 trials, but in some cases more trials were used when details were needed. Three comparison tests kept the frequency of the external pulser constant while the internal pulser's frequency was varied, and the remaining three did the opposite. Assuming that it is unlikely that both clocks are equally inaccurate, the tests will help to suggest the precision for which the internal pulser can be taken to be accurate. As long as both clocks agree (that is, each trial in a test gives the appropriate integer with little or no variation), then it is reasonable to assume that *both* clocks are accurate for that timescale. If the clocks do not agree or the test gives trial results that are more than one count away from what is expected, then both clocks should not be counted on to that precision.

In the first set of tests, the external pulser was kept at a constant 100 Hz, while the internal pulser's frequency was varied. While the internal pulser was at 100 Hz it showed great stability – in 6,439,311 trials, there were only two errors. A linear extrapolation of this error corresponds to an up to 2.68 second drift per day between the two clocks, however it is likely that the drift will be smaller than that. At 100 kHz, the pulsers continued to agree for the most part. About 4,000 errors in 63,084 trials suggests an error occurs about once every 16 trials. Since the PMT's natural firing rate is 20kHz and there are still no errors more than one count off: this is good. When the internal pulser is set to 2 MHz, there is finally an interesting distribution of data. The distribution is somewhat Gaussian, but is unexpectedly shifted somewhat toward the left – although it is worth noting that it is on the right that the trial with the greatest error occurs. It is as if the histogram has a tail. For this setting, the pulser is not very stable.

In the second set of tests, the internal pulser was kept at 2 MHz, while the external pulser's frequency was modified. When the external pulser was set to 100 kHz, there is a lot an equal amount of variation on both sides of the expected value. It is very similar to what was seen in the second test of set one: there are about 1,000 errors in 48,039 trials, but no one error is more than one count off. At 10 Hz, there is a familiar shifted exponential distribution as was seen in the third test of set one (note: to make the shift in the Gaussian easier to see, this graph has been left with a non-exponential y-axis). Finally, at 1 Hz, another characteristic Gaussian curve can be seen, but this time the shift is very clear.

It is my hypothesis that the non-Gaussian shape is because the actual shape is more accurately described by a Poisson distribution that has been made discrete by the histogram. If this is the case, it might explain the skew of each graph and the slight tail found at high counts.

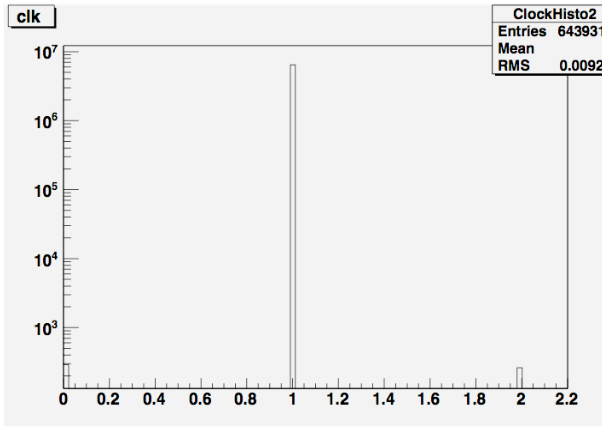


Figure 12: 100 Hz internal pulser vs. 100 Hz external pulser

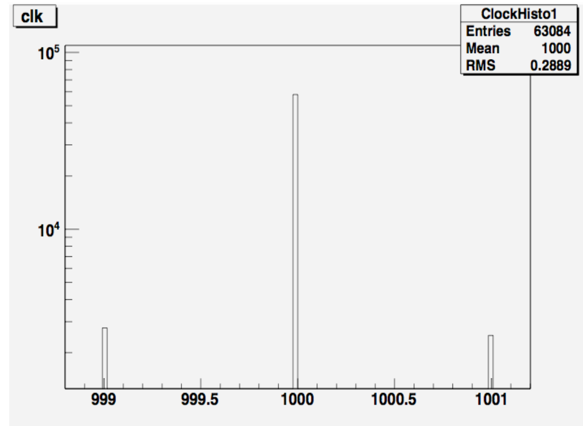


Figure 13: 100 kHz internal pulser vs. 100 Hz external

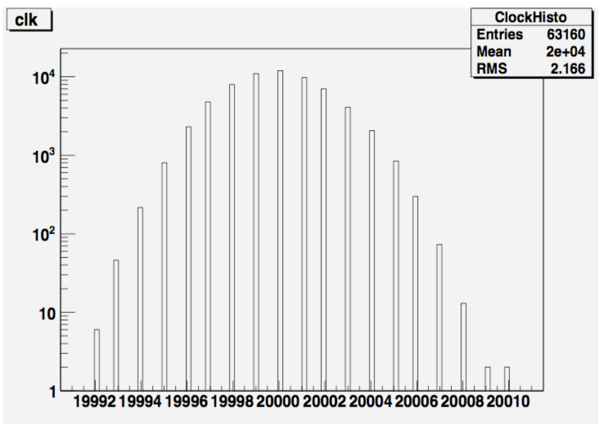


Figure 14: 2 MHz internal pulser vs. 100 Hz external pulser

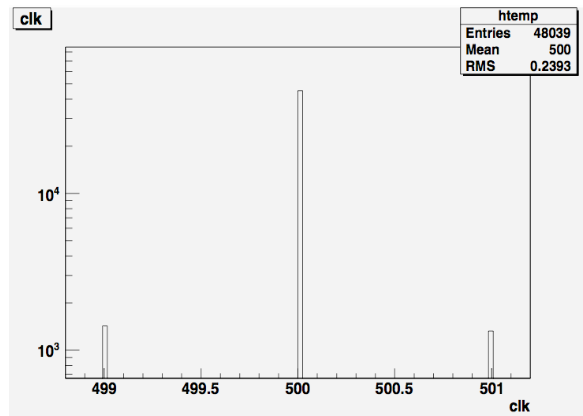


Figure 15: 2 MHz internal pulser vs. 1 kHz external pulse

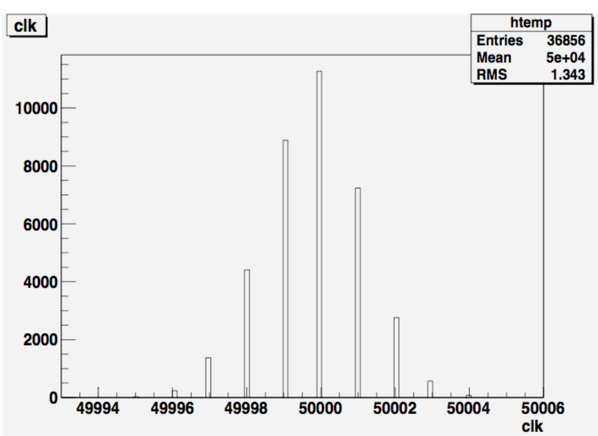


Figure 16: 2 MHz internal pulser vs. 10 Hz external pulser

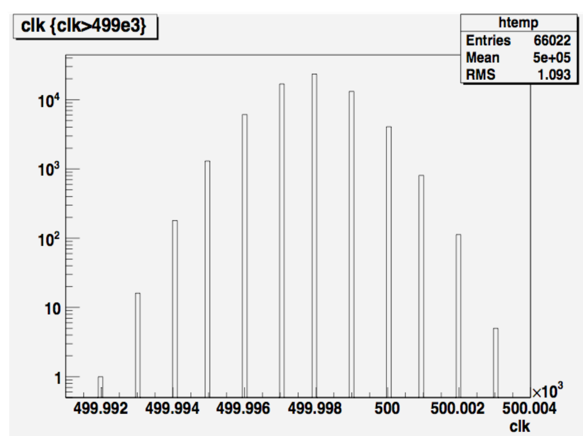


Figure 17: 2 MHz internal pulser vs. 1 Hz external pulser

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